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LAUNCH VEHICLE SYSTEMS COST MODEL

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Future Projects Office

NASA

George C. Marshall Space Flight Center, Huntsville, Alabama

TECHNICAL MEMORANDUM X-53136

LAUNCH VEHICLE SYSTEMS COST MODEL EXECUTIVE SUMMARY REPORT

By

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ABSTRACT

The purpose of this report is to summarize the results of the FY 1964 Launch Vehicle Cost Model Studies. The objective of the study was to develop a computerized detailed mathematical cost model which could yield complete research and development, facility, and operational cost estimates for present and proposed NASA launch vehicle systems. The report outlines the scope of the model, lists the capabilities and limitations of the model, and presents the author's conclusions based on study results, and gives recommendations for future work.

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EXECUTIVE SUMMARY REPORT

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FUTURE PROJECTS OFFICE
RESEARCH AND DEVELOPMENT OPERATIONS

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SUMMARY

The purpose of this report is to summarize the results of the FY 1964 Launch Vehicle Cost Model Studies. The basic objective of the studies was to develop a detailed mathematical cost model which would yield best possible approximations for research and development, facilities, and operational cost estimates for both present and proposed NASA launch vehicles systems. Expendable as well as reusable launch vehicles can be evaluated with the help of this model. For maximum benefit and utilization, the model was programmed on an IBM 7094 computer and is operational at MSFC.

Technologies up through 1980 were considered and include liquid, solid, and nuclear systems. A set of general cost categories were developed to represent all cost, from "cradle to grave," so that a consistent approach could be used in costing vehicle systems. For each cost category, over 80 in all, an analytical functional relationship was developed that would yield cost when appropriately applied. These costs were then synthesized to yield cost in the detail desired.

The recommended future work includes updating and improving the relationships of the present model, as well as extending the time under investigation to 1990. This will include a more extensive investigation of advance propulsion, especially in the area of nuclear systems. A more significant error and risk analysis will be included in order to better interpret the outputs of the model. An effort will be made to coordinate this effort with complementary work at MSC on spacecraft cost so a capability will exist within NASA to cost all systems associated with a total space vehicle system.

SECTION I. INTRODUCTION

In July 1963, contracts were awarded to General Dynamics/Fort Worth and Lockheed California Company to develop a generalized Launch Vehicle Cost Model. The model was to be developed, documented, computerized, and checked out by the contractors in sufficient detail so that MSFC personnel could operate the model without assistance from the contractors.

Historical methods of cost projections are not sufficient for the complex and advanced systems that appear feasible within the next 20 years. To fulfill the planning requirements of completeness, accuracy, and minimum preparation time, the model contains the more advanced techniques of costing with the advantages of high speed computers.

The model will accept, as inputs, physical and performance characteristics of launch systems, as well as operational schedules, time phasing, etc. These inputs are related to costs by means of the mechanisms of the functional relationships contained in the model; as a result of the relationships developed, the model will provide outputs that may be used to make a systematic, quantitative analysis of cost trade offs with design, performance, time, reliability, and other parameters. The estimating flexibility of the model provides a reliable measure of launch vehicle costs for use in planning.

This effort was accomplished under contracts to Lockheed California Company (NAS8-11008) and General Dynamics/Fort Worth (NAS8-11006). The total cost of the two studies was $208,000, i.e., eight direct engineering man-years, and the contract period was from June 1963 to June 1964 (12 months).

The detailed work summarized in this report is documented in the following reports:

1. "Launch Vehicle Systems Cost Model (U)," Volume I (FZM-4150), 27 May 1964, and Volume II (FZM-4154), 15 June 1964, General Dynamics/ Fort Worth.

2. "Launch Vehicle System Cost Model (U)," LR 17827 and LR 17825, June 15, 1964, Lockheed California Company.

These reports may be obtained from the Scientific and Technical Information Division, Code ATSS-A, National Aeronautics and Space Administration, Washington, D. C. 20546.

The technical supervision for the effort was provided by a management team made up of representatives from MSFC, MSC, and NASA Headquarters.

SECTION II. SCOPE AND OBJECTIVES OF THE STUDY

The principle objective of the study was to develop and program a detailed analytical launch vehicle cost model which would operate on an IBM 7094 computer. The following criteria were used as guidelines for the model development.

1. Cost would be computed by categories,

2. Provisions for inflation would be considered in cost projections,

3. Error analysis would be contained in the model structure,

4. FORTRAN (formula translation) programming language would be used exclusively in programming the model,

5. Technologies up to 1980 would be considered,

6. The model would yield total program cost,

7. The model would contain a sub-routine to evaluate vehicle effectiveness,

8. Vehicle payload would not be considered as a cost category.

The scope of this study was broad because the cost model had to be capable of determining costs in all phases of a launch vehicle program. This "cradle to grave" range of consideration included design, development, testing, facilities, and operational costs. The model resulting from this effort is capable of estimating total program costs and major sub-category costs, such as the cost of engine test operations, static test stands, launch pads, and other similar program sub-categories. The challenging demands inherent in launch vehicle cost estimating are met by this model, which offers an accurate, versatile, and usable mathematical tool to aid in the long range planning needs of NASA.

The cost model developed provides: (1) a mechanism for cost estimation, (2) a measure of cost effectiveness, (3) a cost sensitivity gauge, (4) guidelines for resource planning and allocation, and (5) help in coordination of mission development schedules with program funding.

SECTION III. METHOD OF APPROACH

There were two major tasks in developing the cost model: (1) develop a model structure with the inherent flexibility to meet its intended use; and

(2) formulate functional relationships or equations which describe, mathematically, the causative mechanism that link design and performance to cost. Each of these tasks are discussed separately below.

A. MODEL STRUCTURE

In formulating the model structure, adequate consideration was given to the major events required in the development and use of a launch vehicle. These events are reflected in the basic elements of the model structure, which form the major framework within which costs are analyzed. This structure includes: (1) a research and development sub-model; (2) an operational sub-model; and (3) a facilities sub-model. The planning analyst has the option of using any one or combinations of these three sub-routines in his cost analysis.

The research and development sub-model has two major divisions. In the first division, a computation is made of the elements or units, e.g., number of tests, facilities, new hardware spares, etc., that affect cost. In the second division, the cost of the research and development phase by time period is computed.

The operations sub-model is tied directly to the launch calendar, which is an input to the model. In the operations sub-model, the number of facilities by type required in each time period is computed; also, cost of hardware propellants, launch and assembly, sustaining engineering, and other miscellaneous operating functions are computed.

The facilities sub-model is the third and final major component in the basic Launch Vehicle Cost Model structure. In this sub-routine, the costs of facilities for manufacturing, sub-system tests, stage tests, launching, and support can be computed. The output includes data on the costs of facilities by time period, and data on total facilities, by types, required for each launch vehicle configuration. There is a provision for by-passing this sub-model if estimates of the cost of facilities are not required.

After the three major sub-models were formulated, a wide variety of other sub-routines, options, and program constraints were considered; those found to be of value were integrated into the Launch Vehicle Cost Model. Among the sub-routines included are measurements for cost effectiveness analyses, reliability assessment, learning curve relationships, inflationary adjustments, error analysis, time phasing adjustments, and other pertinent factors that highly effect cost projections. The inclusion of these sub-routines expanded the model's flexibility to provide conceptual evaluation, and increased the scope of vehicular development planning. Concurrent with the integration of these special subroutines, provisions were made for a data library in the model. Development of the data library permits the streamlining of input requirements, because all input data can be stored for use in future problems. As an additional feature, the data library allows updating of vehicle parameters or functional relationships without disturbing the basic model. After establishment of the data library, input requirements are reduced because only major descriptive inputs are needed for computer runs.

This approach of model development had several advantages which resulted from the model's having been divided into two distinct parts, the logic structure (main body) and the data libraries including the functional relationship library. This division allowed the logic structure to be programmed before all relationships were developed. It also permits easy updating or addition of relationships without changing the logic structure.

Some considerations and comments regarding the model development and its use are discussed in the subsequent paragraphs.

1. Error Analysis

All cost computed by the cost model are considered to be mean values. An error analysis procedure was developed for use in determining the probable error that might be incurred by the model estimating techniques. To conveniently handle the accumulation of error, and to avail the difficult estimation of dependence among error distributions, points within the model were selected that are assumed to be independent. Using this assumption, a procedure was developed to provide a probability statement based upon the normalized error distribution for the total cost estimate generated by the model.

2. Cost Effectiveness

Cost effectiveness is expressed in terms of dollars per pound of delivered effective payload. These measures are computed in three forms: (1) direct operating cost effectiveness, (2) cumulative operating cost effectiveness, and (3) total operating cost effectiveness. These cost effectiveness routines provide a valuable tool for the evaluation and comparison of vehicle configurations.

3. Time Phasing

An incremental funding concept was selected for the model. This concept allows obligations and/or expenditures to be computed on a semi-annual or annual basis. Typical obligation curves were developed using historical data from previous programs, and lead times were determined for commitments to obtain the necessary funding. The total cumulative funding curve is constructed for the major components of cost, such as airframe, propulsion, astrionics, launch operations, etc., by relating the curve to major milestones in the program.

4. Inflation

No readily available index, tailored for the space vehicle industry, was available for use in the model. Common indexes for cost of living, retail prices, and wholesale prices were too aggregate to be applicable to aerospace activities. Therefore, a general aerospace index was devised for the space vehicle industry with specific sub-indexes applicable to research and development, facilities, and operating costs. The general aerospace index will be applied when the data to be adjusted are not specifically categorized into research and development, facilities, or operations costs. However, if costs are categorized, a more precise inflationary adjustment will result from the application of the individual sub-indexes.

5. Inputs

The majority of the input data consists of standard design and performance parameters commonly developed in studies and for presentation in proposals and technical reports. There are three types of inputs required to exercise the model: (a) library data, or the physical and performance data that describes the systems to be analyzed, and other parameters that do not change frequently, such as transportation rates, etc.; (b) problem required data, or parameters which change with every problem such as schedules, launch rates, etc.; and (c) problem option data, i.e., data required to override some automatic computation in the model.

6. Outputs

There are provisions in the model for eight basic print-out formats. The eight formats all represent degrees of detail in cost, cost effectiveness, and error analysis. These eight formats can be exercised on the stage, vehicle, or total program. A detailed list of possible outputs can be found in Volume II of the General Dynamics final report (FZM-4154) referenced in Section I.

7. Computer Program

The cost model is programmed in FORTRAN IV and MAP languages, and operates under the IBJOB processor within the IBM 7090/7094 IBSYS monitor system. This procedure can be operated as a standard job at the MSFC Computation Laboratory. The flow charts, program listings, and instructions for this procedure are documented in a Digital Computer Manual available at MSFC. The average computer time required to calculate the cost of a single launch vehicle (one data point) is two minutes.

B. FUNCTIONAL RELATIONSHIPS

A very fundamental part of this task was, first, to determine the cost categories for which relationships would be developed. One of the overriding criteria for this selection was that each category should apply to all technologies, and should be all inclusive and mutually exclusive. A complete list of the categories in the model can be found in Volume II of the General Dynamics final report (FZM-4154) referenced in Section I.

Another factor that influenced functional relationships was the availability of data. Raw data were collected from 26 independent sources and were collated, refined, and interpreted. Data too vague or gross to fit the rigorously defined cost categories were discarded.

The functional relationship, which related cost to design and performance parameters of the vehicle systems, were derived principally through a regression analysis when sufficient data existed. However, some of the more advanced technologies required development through empirical analysis and extrapolation of data from present programs. The total number of cost estimating functional relationships presently incorporated into the model is 125. This number does not include all the built-in relationships which calculate hardware requirements, resources, stage and vehicle reliability, etc.

Some discussion of data analysis and selection of variables are presented in the following paragraphs.

1. Data Analysis

Because a high degree of accuracy was desired in developing the functional relationships, data refinement was considered to be a critical step toward this goal. Despite the care taken in preparing specifications, virtually all cost and performance data analyzed were not comparable in the strictest sense. All data were thoroughly examined, collated, and refined so that data in each category were internally consistent.

Typical problems encountered in the data analysis were:

(a) Collected data represented cost of programs which occurred at different times which made inflationary and other time related factors different for each data point.

(b) Data supposedly representing the same categories of cost actually contained widely divergent items.

(c) The accounting systems from which data were gathered differs in each organization.

(d) Data transformation from one source to another resulted in interpretation which, in some cases, did not always result in true cost.

This task in developing the functional relationships was one of the most important and time consuming in finalizing the model.

2. Following the collection and collation of data, the next step taken in the development of functional relationships was the investigation and selection of cost sensitive variables. This selection process was divided into three phases, each of which was repeated several times before the functional relationship was developed. These phases were: (a) determine the general types of variables to be used, (b) determine proper values to be used for the selected variables, and (c) test the desired function to determine its goodness of fit.

Statistical considerations place a limitation upon the number of variables that may be dealt within any one relationship. In deciding upon the number of variables to be used in the final relationship, it was necessary to compromise among the demands for accuracy, i.e., the desire to reduce inputs and the requirements of model storage. For example, the most accurate functional relationship for liquid engines production cost used five variables, but, because two of the five variables were difficult to input and did not add significantly to the estimating accuracy of the relationship. Those two were discarded and only three variables were used in the final functional relationship. In establishing the final form of relationships, impirical judgment and standard statistical measures were used. All relationships were tested and checked through the use of hypothetical, but typical, values for the independent variables. In the course of making the apprisal of the final relationships, no illogical cost estimates were observed for a reasonable range of values. The total number of variables within the present model is 241.

SECTION IV. APPLICATIONS

As a tool to aid the decision maker, the model will have many uses beyond the usual cost analysis type problem. The following are examples of these applications as well as general comments on the use of the model:

1. The most obvious use of the model is to estimate costs of system concepts which are generated within MSFC, or to assess the accuracy and reliability of cost predictions furnished MSFC from other sources.

2. Trade studies for competitive conceptual designs are another useful application of the cost model. Post-Saturn vehicles will undoubtedly require many such studies. Not only will cost effectiveness implications require assessment, but also the resource requirements (facilities, personnel, etc.) associated with such programs.

3. Trade studies for cost effectiveness purposes are frequent applications of the model. Cost effectiveness studies involving Titan III, Saturn IB, and Saturn V are typical examples. Another example would be studies that attempt to determine the content or "mix" of the most efficient combination of vehicles to accomplish the long range NASA goals.

4. The model is very useful for cost sensitivity studies where the dollar implications of changes in performance, design, reliability, etc., may be measured.

5. Mission planning studies are important applications for the model and are similar to the sensitivity studies mentioned above. The primary objective of a mission planning study is to assess the implications of launch schedules on costs. Launch schedules for planetary missions can vary greatly for the same mission when the unfavorable time periods are considered.

6. Budget planning will be involved in all of the above but also require separate studies. The cost model makes it possible to integrate long range technical planning with financial planning.

One point that should be emphasized is that a cost model is not designed to replace the cost analyst, but is designed to assist him in increasing his capabilities. The flexibility that is being built into the Launch Vehicle Cost Model permits the cost analyst to employ all his skills and knowledge in the solution of a cost problem. The cost analyst defines the cost problem associated with any given decision problem, specifies all related parameters and program constraints, and obtains, from technical sources, estimated design and performance variables. The utilization of the cost model frees the analyst from burdensome computation so that he may apply all his talents to analysis. Not only does the employment of a cost model offer rapid, objective, and complete answers to cost problems, but it also provides the only practical way for the cost analyst to cope with the mounting workload brought about by the increasing employment of cost as a value criterion in decision analysis.

To enhance the model utility, the model will provide rapid cost estimates for a wide range of launch vehicles of varying sizes and technologies. The model has been constructed so that major cost categories represented by sub-models can be input and evaluated separately. The model structure and programming has been formulated so that extensive revisions to the model structure or the computer program are not required when updating is necessary.

Model design, programming, and derivation of estimating relationships have progressed to the point that certain statements can be made, with confidence, concerning the capability of this cost model, its applications, accuracy, and growth potential.

The completed model, program deck, and cost manual represent an important step in fulfilling NASA's needs for an accurate, versatile, and usable model for predicting launch vehicle systems cost, although this is not a panacea for solution of all cost problems.

It should be recognized that the Launch Vehicle Cost Model is not a simple model. Requirements for versatility, wide range of applications, accuracy, and responsiveness to a rapidly advancing space technology dictates the level of complexity. A compromise in complexity was obtained through the use of bypass options, capability of handling varying levels of detail, modular instruction to allow use of only specific parts of the model, provisions for insertion of actual costs rather than calculations, and storage of commonly used data. These features enable the model user to select the level of complexity.

SECTION V. RECOMMENDED FUTURE WORK

Based upon the capability and limitations of the present cost model the following is recommended for future work:

1. Improve and expand the functional relationships contained in the present model, which is one of the largest future tasks.

2. Increase the inherent flexibility, accuracy, and capability by including a more detailed error analysis, risk analysis, and by extending the period under consideration to 1990.

3. Increase the capability of the recovery and reconditioning sub-model to handle the sensitive variables internally.

4. The measures of effectiveness should be expanded to include more than dollars/pound. They should include dollar evaluations of yields associated with the orbital, lunar, and planetary missions.

5. A technique for estimating time-cost relationships should be developed and included in order to provide the capability to vary schedules as well as funding within the model.

6. The model should be expanded to account for cost associated with the total mission cost, i.e., the interrelationships between payloads and launch vehicles investigated for mission planning.

7. A technique for resource requirements, which include dollars, manpower, facilities, and materials, should be added to reflect constraints on the program under consideration.

8. Additional cost studies are recommended to support items 5, 6, 7. If approved, these support studies would be done by both MSFC and MSC and results would be available by June 1965. Where appreciable these results should be included in the cost model.

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LAUNCH VEHICLE SYSTEMS COST MODEL
EXECUTIVE SUMMARY REPORT

By T. H. Sharpe

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This report has also been reviewed and approved for technical accuracy.

H. H. Koelle

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Director, Future Projects Office

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